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DSTO-TN-0584

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ABSTRACT

This report outlines an experimental study into the impact of repeated high intensity insonification on the rate of crack growth in Al7075 coupon specimens subject to mechanical tensile testing. The investigation was undertaken to ascertain whether the application of sonic thermography, an encouraging and presumed nondestructive inspection technique, induces a deleterious structural effect. Under a representative inspection regime no evidence was found of an accelerated or otherwise altered rate of crack growth compared to that measured for a benchmark group. It tentatively suggests that the technique is structurally benign when applied to cracked Al7075 components.

Published by

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AR No. 013-213
October 2004

APPROVED FOR PUBLIC RELEASE

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EXECUTIVE SUMMARY

Sonic thermography has recently emerged as an important inspection technique capable of resolving inspection problems that contemporary methods have struggled with, for example tightly-closed cracks in metallic structures and kissing bonds in composite repairs. The technique uses elastic waves injected by an acoustic horn resonating at typically either 20 or 40 kHz, which often excites lateral motion at the surfaces of a defect. This motion induces frictional heating and in turn a thermal indication, which can often be detected with sensitive thermal imaging equipment. Although shown to be quite useful in detecting many types of structural defects, several issues require close investigation and perhaps most critical of these is whether the technique is indeed non-destructive. No published work could be found that examines the impact of high intensity insonification, in the context of nondestructive inspection, on the fatigue crack growth characteristics of structural metals. This is despite an accepted understanding that thermal signatures produced during the intense acoustic excitation can evolve from a mechanically irreversible change of state.

An experimental study was undertaken to examine the impact of repeated high intensity insonification on the rate of crack growth in Al7075 coupon specimens subject to mechanical tensile testing. Under a representative inspection regime no evidence was found of an accelerated or otherwise altered rate of crack growth compared to that measured for a benchmark group. It tentatively suggests that the technique is structurally benign when applied to cracked Al7075 components.

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Kelly Tsoi completed a BSc. (Hons.) in Physics at The University of Melbourne in 1995. She commenced work in the Airframes and Engines division of the Aeronautical and Maritime Research Laboratory in 1996 and has worked on methods of fatigue life enhancement using smart materials. In 1998 she commenced studies at The University of Sydney and Katholieke Universitait Leuven, Belgium in shape memory alloys and their composites, which led to the completion of a PhD in 2002. She is currently a research scientist in the Smart Materials and Advanced Diagnostics group of the Air Vehicles Division, researching novel non destructive evaluation techniques.

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Nik Rajic received a B. Eng. (Hons.) in Mechanical Engineering from the University of Melbourne in 1989. He joined Structures Division at the Aeronautical Research Laboratory in 1991 and in 1992 undertook studies at Monash University which led to the completion of a PhD in 1995. He has since contributed to research on fatigue-life extension techniques, thermoelastic stress analysis, thermoplasticity, thermographic nondestructive evaluation and in situ structural health monitoring techniques based on smart structures principles. He is currently a Senior Research Scientist in the Smart Materials and Advanced Diagnostics group of the Air Vehicles Division.

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1 Introduction

Sonic thermography (ST) is an emerging structural inspection technique potentially well suited to the detection of defects like closed cracks in metallic structures and kissing bonds in composite repairs, where closure of the flaw surface often renders the defect transparent to established methods like ultrasound and flash thermography. The technique uses elastic waves generated by an acoustic horn driven at typically 20 or 40 kHz, which can often excite lateral motion at the flaw surfaces. Under a contact stress this lateral motion induces frictional heating which gives rise to a thermal signature often measurable with sensitive infrared imaging equipment. Evidence of the successful application of the technique to the inspection of both metallic and composite components is readily found ((Mignogna *et al* (1981), Mignogna and Green (1982), Tenek and Henneke (1991), Zweschper (2001)).

Although evidently an efficacious method for some important inspection problems, there are still several key issues to be resolved. One of the most important is the impact high intensity insonification may have on the fatigue properties of a metallic subject. No literature could be found that examines the effect of short term (less than 10 s) insonification on the fatigue properties of metallic specimens. As mentioned earlier, the technique uses intense high frequency acoustic waves to induce the production of heat between the opposing surfaces of a defect. The process is, at least in some part, mechanically irreversible, leading to the possibility that the inspection process may compromise the structural integrity of its subject. A conceivable example of an irreversible mechanical effect is wear of crack face asperities caused by acoustically induced motion under high contact stress. At an extreme, given a sufficiently high dynamic stress level, the acoustic excitation might produce crack growth.

The fact that intense high frequency excitation can lead to damage has been known for some time, evidenced by the use of ultrasonic excitation in accelerated fatigue testing (Mignogna and Green (1982)), Willertz (1980) and Tulyanon and Salama (1976)), where, instead of using the normal fatigue testing approach, intense ultrasonic loading was applied to coupons in order to substantially accelerate testing. The early literature on this topic includes some noteworthy observations. For instance Willertz (1980) noted that an increase in the loading frequency produced an increased endurance limit in certain metals. Mignogna and Green (1982) observed that when a specimen subject to a tensile load was injected with high frequency ultrasound, a softening effect occurred. They determined that it was not due to the heating of the specimen but rather an interaction of the ultrasound with dislocations resulting in an increase in the energy state at dislocation sites.

This report outlines an experimental program designed to assess the effect of intense insonification applied over a short duration ($< 10\,\mathrm{s}$) characteristic of nondestructive inspection, on the growth-rate of cracks in Al7075 pre-notched coupon specimens subject to low-frequency cyclic mechanical loading. The performance of the technique in detecting cracks was also examined, as was the effect of specimen thickness on the crack signature.

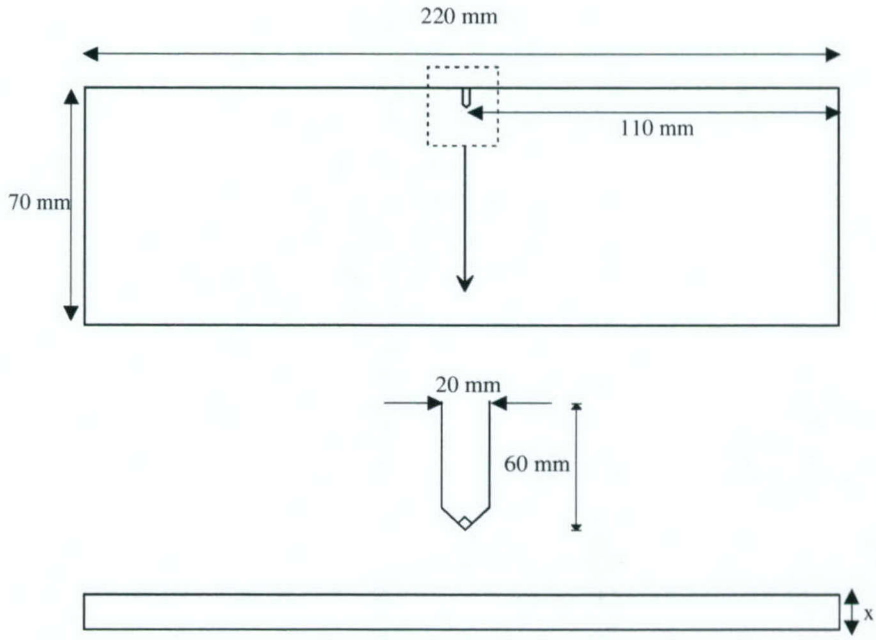

Figure 1: Specimen dimensions. x is the thickness of the specimens: 1.6 or 3.2 mm.

2 Experimental Setup

2.1 Specimens

Testing focused on 7075 aluminium alloy coupons with the dimensions indicated in Figure 1. In order to examine the effect of specimen compliance, coupons were produced in two plate thicknesses: 3.2 mm and 1.6 mm. All samples contained a 6 mm long side notch to facilitate crack initiation.

2.2 Acoustic Horn

The acoustic horn used in this investigation is a commercial hand held plastic welding unit designed for resonant operation at 20 kHz. Optimised for welding plastics, the horn is unlikely to yield optimal performance across the broad range of aircraft structural materials since, by matching the impedance at the probe tip to plastics, the transfer of acoustic energy into other materials is compromised. Improved transfer can, however, be achieved by introducing a sufficiently compliant material between the probe tip and the test subject. In this study, a thin layer of felt was selected on the grounds of an earlier investigation (Tsoi and Rajic (2004)), which showed that amongst a range of interface materials, felt tended to produce, on average, the highest observable thermal signatures in aluminium alloy specimens.

The application of the acoustic pulse was synchronised with the infrared image capture system using software developed in-house. The horn was operated at full power, which is

Table 1: Table showing loading forces for the specimens.

Thickness	F_{min} (kN)	F_{max} (kN)
3.2 mm	1.6	10.67
1.6 mm	0.8	5.33

a nominal 500 W, and the insonification period was kept fixed at 10 s. Thermal image capture occurred at 15 Hz for 300 frames, corresponding to an inspection time of 20 s.

2.3 Infrared Camera

Infrared imagery was acquired using a Raytheon Radiance HS system. The infrared focal plane array is cryogenically cooled and has 256 x 256 indium antimonide detectors with a sensitivity of 0.02 K in the wavelength band of 3-5 μm. The detectors operate in snap-shot mode with user controlled integration time and frame rate. The latter can be varied from a maximum of 140 Hz for a 256 x 256 array to 2 kHz for a central 64 x 64 sub-array.

2.4 Mechanical Testing Apparatus

Fatigue tests were carried out on a 100 kN MTS mechanical test machine. The specimens were tested at a loading frequency of 10 Hz. Table 1 shows the loading forces used for the two specimen types. The crack length was measured at regular intervals of 1000 cycles with a static load of 0.75 times the maximum force, F_{max}, as shown in Table 1, applied in order to open the crack slightly for a more accurate length measurement.

For each type of specimen, 10 samples were mechanically cycled in order to establish a benchmark crack growth characteristic. During each test, cycling was suspended at crack lengths of 5, 15 and 25 mm, for a duration of approximately 5 minutes to reflect the frequency and duration of the thermographic inspection process. This was done in order to determine the effect of a short cessation of loading on the crack growth rate so as to exclude it's effect when comparing the baseline results with those of the inspected group. Having established the crack growth behaviour for the control group, the remaining specimens of each thickness were then exposed to the same loading regime except that insonification was applied, as already mentioned, at 5, 15 and 25 mm $\pm$ 5 mm crack lengths. During each insonification event thermal imaging was undertaken to record the signature of the crack. Figure 2 shows a photograph of the experimental arrangement. A spring was used to maintain a constant force between the specimen and the probe. It has been shown elsewhere (Tsoi and Rajic 2004) that the force applied to the acoustic horn has a measurable and important effect on the thermal response.

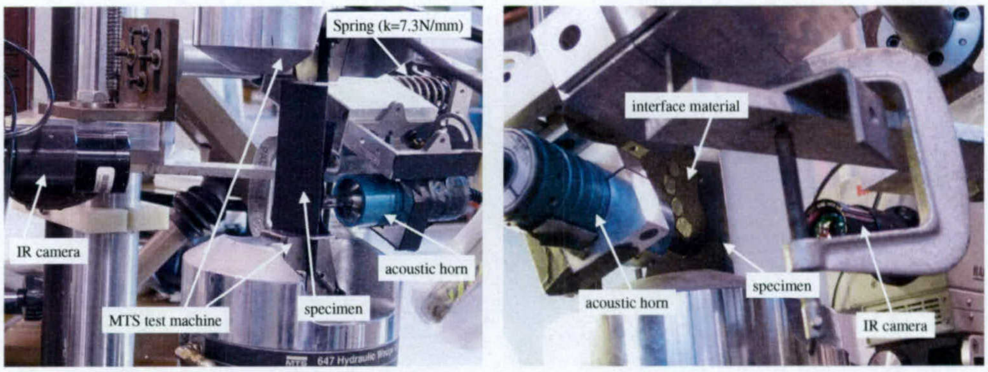

Figure 2: Photographs of the experimental setup showing the specimen clamped in the MTS machine, the acoustic horn and the thermal camera.

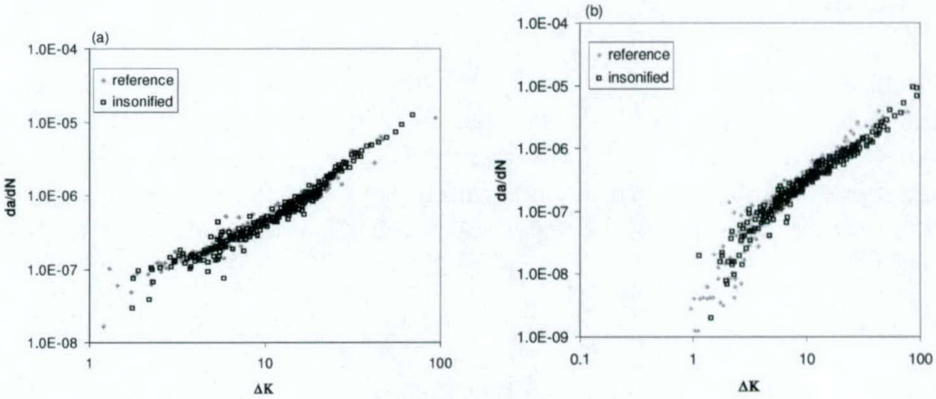

Figure 3: Crack growth rate curve for 1.6 mm and 3.2 mm thick specimens, respectively, showing reference and insonification at 5, 15 and 25 mm crack lengths, for 10 s.

3 Results

Figure 3 shows the crack growth rate for reference and insonified specimens of 1.6 and 3.2 mm thickness, respectively. The overall crack growth characteristics for both types of specimens is similar with little evident variation between the reference and the insonified groups. To facilitate a crude quantitative measure of variation, both sets of data were fitted to a Paris-Erdogan type expression relating stress intensity factor to the crack growth rate. It takes the form

$$\frac{da}{dN} = C(\Delta K)^n \tag{1}$$

where C and n are material constants, $\frac{da}{dN}$ is the crack growth rate and ΔK is the stress intensity factor range. The material constants, C and n, were determined from the crack growth data using a least squares approach. Figure 4 shows the average of these values for the reference and insonified coupons. The error shown corresponds to one standard deviation. At this level of variation there is little statistical difference between the reference and insonified sets.

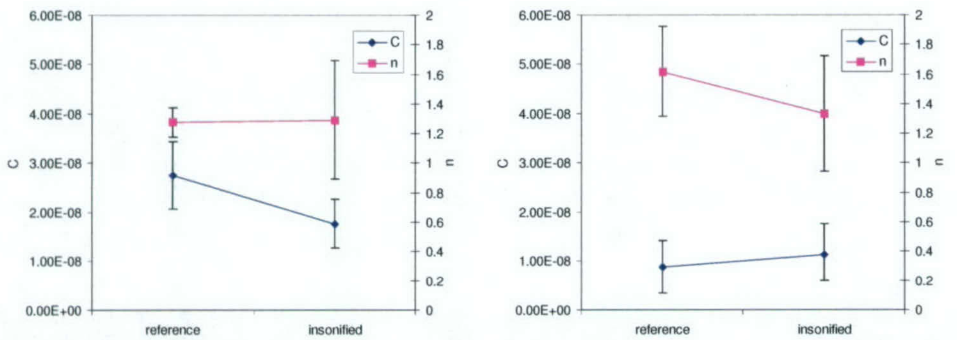

Figure 4: The average values of the material constants n and C for reference and insonified coupons for the 1.6 mm and 3.2 mm thick specimens, respectively.

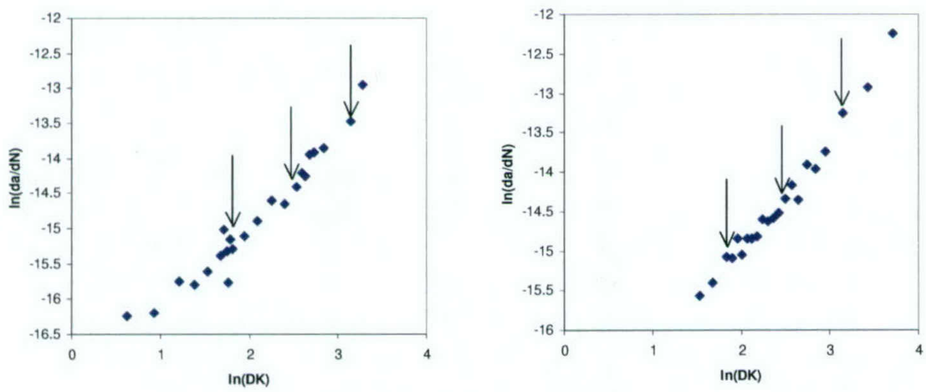

Figure 5: Representative crack growth data for reference and insonified coupons, respectively. The arrows indicate stoppages at 5, 15 and 25 mm crack lengths, from left to right, respectively.

Whilst it appears evident from this straightforward analysis that insonification has led to no sustained impact on the crack growth rate, it does not rule out the possibility of a transient effect. To examine this, the crack growth data was more closely scrutinised in the phase immediately following the insonification. Figure 5 shows representative crack growth curves for a reference and insonified specimen. As described earlier, the loading regime for the reference specimens included periods where the load was suspended at crack lengths of approximately 5, 15 and 25 mm, to mirror the procedure applied to the insonified group. From the reference curve it can be seen (arrows) that the brief cessation produced no convincing systematic change in the crack growth curve beyond the general scatter. The insonification curves show that at the same intervals there is similarly no evidence of a systematic change which suggests the insonification has had little effect.

3.1 Thermal Imaging

Figure 6 shows raw thermal images of a representative 1.6 mm thick coupon, 1 s into the insonification. A strong indication is apparent, and interestingly, in relation to the last image the rate of heat generation varies along the crack and is evidently most intense at roughly the mid point in the crack wake. The emission from the crack tip itself by contrast is much weaker, suggesting the insonification has had far less impact in this critical region.

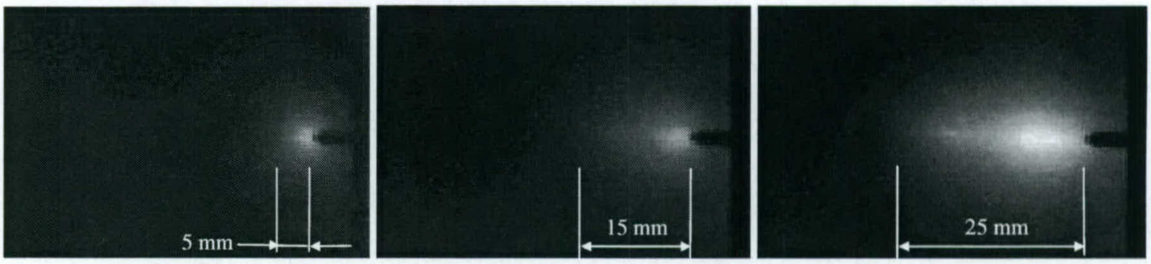

Figure 6: Raw thermal images of a representative 1.6 mm thick coupon showing the crack for increasing crack length of 5mm, 15mm and 25 mm respectively,1 s into the insonification.

Figures 7 (a), (b) and (c) show equivalent raw thermographs for a representative 3.2 mm thick coupon at three different crack lengths: 5 mm, 15 mm and 25 mm. In comparison to the 1.6 mm thick coupons, the thicker specimens produced a far weaker thermal signature which necessitated an additional processing step. Principal component thermography, described elsewhere (Rajic (2002)), was applied, leading to the accompanying set of thermographs (Figures 7(d), (e) and (f)) where much stronger indications are evident. Interestingly, the principal component thermograph for the 25 mm crack reveals an unexpected vertical asymmetry with respect to the crack. This in fact is caused by forced lateral heat flow from the acoustic source located some 4 mm below the lower boundary of the frame. Such forced lateral flow provides yet another thermal means of detecting cracks, and is an approach currently being pursued (Rajic (2004)).

The necessity for image enhancement in the case of the thicker specimens is indicative of a much lower rate of heat production at the crack faces compared to the 1.6 mm specimens. This confirms that specimen structural compliance is an important factor in determining the intensity of a thermal signature.

4 Conclusion

Evidence gathered in this study indicates that for the excitation parameters considered, sonic thermography has no deleterious impact on the fatigue characteristics of Al7075 coupons. Based on the much higher average thermal signatures recorded for the 1.6 mm specimens, any impact, if present, would likely be most evident for these specimens. No such impact was found.

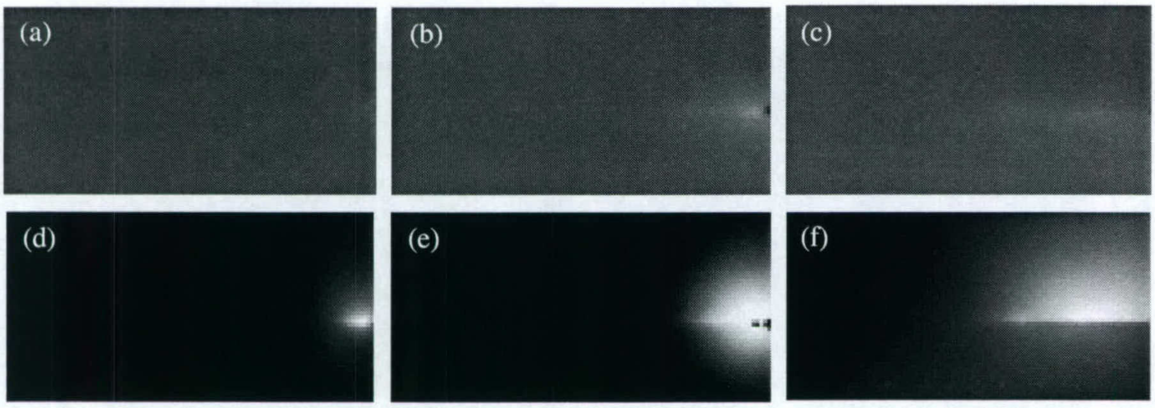

Figure 7: Raw thermal images (a, b and c) and corresponding principal component thermographs (d, e and f) of a representative 3.2 mm thick coupon at crack lengths of 5, 15 and 25 mm, respectively.

5 Acknowledgments

The authors would like to acknowledge Mr David Rowlands and Mr Brian Jones for their help with the experimental work carried out during this investigation.

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2. TITLE Effect of Sonic Thermographic Inspection on Fatigue Crack Growth in an Al Alloy		3. SECURITY CLASSIFICATION Document (U) Title (U) Abstract (U)		
4. AUTHORS Kelly A. Tsoi and Nik Rajic		5. CORPORATE AUTHOR Platforms Sciences Laboratory 506 Lorimer St, Fishermans Bend, Victoria, Australia 3207		
6a. DSTO NUMBER DSTO–TN–0584	6b. AR NUMBER 013-213	6c. TYPE OF REPORT Technical Note	7. DOCUMENT DATE October 2004	
8. FILE NUMBER M1/9/1338	9. TASK NUMBER LRR 03/157	10. SPONSOR CDS	11. No OF PAGES 8	12. No OF REFS 11
13. URL OF ELECTRONIC VERSION http://www.dsto.defence.gov.au/corporate/reports/DSTO–TN–0584.pdf		14. RELEASE AUTHORITY Chief, Air Vehicles Division		
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18. DEFTEST DESCRIPTORS Nondestructive tests, thermography, fatigue tests, crack propagation, Aluminum alloys, acoustics				
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TECHNICAL NOTE DSTO-TN-0584 AR-013-213 OCTOBER 2004

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